

IMPLICATIONS OF
CONFINING FORCE FIELD STRUCTURES
IN HARD HADRONIC PROCESSES

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 Implications of Confining Force Field Structures
 in Hard Hadronic Processes

SAMMANFATTNING

This thesis is centered on the study of confining force field structures in hard scattering processes. Perturbative QCD provides the means of calculating any process on the parton level, but to be able accurately to describe the actual outcome of an event, one still needs a phenomenological model for how quarks and gluons transform into observable hadrons. One such model is based on the assumption that the particles are produced by the confining fields stretched between the partons. The actual particle distributions will then depend on the topology of the confining fields. We have developed a Monte Carlo program to simulate complete events in hard scattering, and we use this to study the properties of the confining field in different trigger situations. We further look at the amount of hard processes that can be expected in experiments that trigger on transverse energy sum (calorimeter experiments). Finally, we investigate charm production within our model.

NYCKELORD

Hard scattering, perturbative QCD, colour field structure, soft hadronization, Monte Carlo

DOKUMENTTITEL OCH UNDERTITEL – SVENSK ÖVERSÄTTNING AV UTLÄNDSK ORIGINALTITEL
 Konsekvenser av fjättringsfältets struktur i hårda hadroniska processer

TILLÄMPNINGSSOMRÅDE

Grundläggande kartläggning av fullständiga händelser i hårda partikelkollisioner. Jämförelser med experiment (partikeldistributioner etc.) för att testa QCD. Simulering och utformning av experiment för att studera fjättringsfältets natur.

NYCKELORD

Hårda partikelkollisioner, QCD, datasimulering, partikeldistributioner, fjättringsfältets natur

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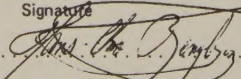
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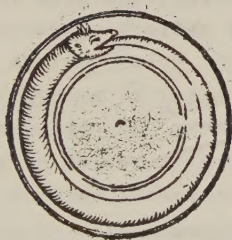
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Qui nos rodunt confudantur
et cum iustis non scribantur.



This thesis is based on the following publications:

I H.-U.Bengtsson

The Lund Monte Carlo for High- p_T Physics

Lund Preprint LU TP 82-15

II B.Andersson, H.-U.Bengtsson, G.Gustafson

Event Structure in Reactions With Prompt Photons

Lund Preprint LU TP 82-10

III T.Åkesson, H.-U.Bengtsson

Transverse Energy Distribution and Hard Constituent
Scattering in Hadronic Collisions

Phys.Lett. 120B (1983) 233



IV B.Andersson, H.-U.Bengtsson, G.Gustafson

Charm Production and the Confining Force Field

Lund Preprint LU TP 83-4

1. Introduction

δύο δὲ μόνῳ καλῶς συνίστασθαι
 τρίτου χωρὶς οὐ δυνατόν· δεσμὸν
 γὰρ ἐν μέσῳ δεῖ τινα ἀμφοῖν
 συναγωγὸν γίνεσθαι.

Plato: Timaeus 31 b-c

The Greek noun κόσμος has two distinct meanings, as can be gathered from its later derivatives cosmology and cosmetics: order and 'a thing of beauty.' To the Greeks, however, the two concepts were inseparable, beauty implying a high degree of order, order creating an impression of beauty. Consequently, when the natural philosophers of Ionia began to explore Nature, they based their theories on principles of symmetry and regularity, imparting to Universe itself the name of κόσμος to signify its perfectly ordered structure. One way to realize this ideal of 'beauty-in-order' was to consider all things of heaven and earth as symmetric arrangements of fundamental constituents. Thus was born the concept of the atoms, the indivisible building-blocks which make up the observed world in all its rich and varied aspects. Already the Pythagoreans had attempted some such explanation, with the atoms mathematical points, but it took the genius of Leucippus (Λεύκιππος) and Democritus (Δημόκριτος) of Abdera (the exception to prove the rule: the Abderites were otherwise endowed with a proverbial stupidity) to formulate the theory in terms of physical building-blocks. The teachings of these early atomists have unfortunately been handed down to us only through the (admittedly beautiful) hexameters of the later Roman epicurean Lucretius, but a benevolent reading of his De rerum natura seems to indicate that the model incorporated such important principles as the conservation of matter and the universality of physical laws. True to their philosophical view of life, the Greeks had not the interest (nor, in all fairness, the means)

to test the hypothesis experimentally, and it was left to the scientists of the nineteenth and twentieth centuries to prove the validity and, paradoxically, the erroneousness of the atomic concept.

Investigations, notably by Dalton, indeed showed matter, i.e. the elements, to be built up from atoms, but, as later experiments proved, atom was a misnomer, for atoms were not indivisible. The existence of the electron was implied already in the works of Faraday; scattering of α -particles on gold foil (Rutherford 1911) gave proof that the atomic 'balls', whose dimensions were $\sim 10^{-10}$ m, had almost all of their mass concentrated to a positively charged nucleus of radius $\sim 10^{-14}$ m. Eventually, a new level of fundamentality was reached: matter was built up from atoms, and atoms from protons, neutrons and electrons, the 'partes partium' or elementary particles. To explain the energy spectrum in β -decay, one further particle, the neutrino, had to be postulated (Pauli 1930). Counting also anti-particles and the quantum of light, the photon, this gave a grand total of nine elementary particles.

This picture was not to remain unshattered, however. To understand the force that holds the nucleus together, the strong force, Yukawa in 1935 proposed the existence of a mediator particle with a mass around 100 MeV. This particle, the π -meson, was duly found, but its discovery triggered an avalanche of new findings: whole sets of particles every bit as fundamental as the old ones. Elementary particles were becoming as numerous as all Rabbit's friends-and-relations, literally flooding the data tables.

'- Three quarks for Muster Mark!' In 1964, Murray Gell-Mann and George Zweig showed that the vast majority of the elementary particles, namely those partaking of the strong force: the hadrons, could be simply described as composites of still more fundamental objects, called quarks for the three kids that sometimes take the place of Mr. Mark in the novel *Finnegan's Wake* by Joyce. Baryons, like the proton, consisted of three quarks (whence the analogy); mesons, like the π , of a

quark and an antiquark.

The quarks had strange properties. First and foremost, their charge had to be fractional, a fact that would make them easy to detect. A regular 'Hunting of the Quark' was launched, but no such beast was found roaming at large, and enthusiasm over the quark concept was somewhat subdued. However, at SLAC, the proton was seen to have a grainy structure, so maybe there were quarks after all, albeit not free ones? 'Two objects cannot well be held together by themselves without a third,' writes Plato in *Timaeus*, 'for there has to be a bond joining the two.' Physicists had been studying models for the forces between quarks in the context of non-abelian gauge theories, and in 1972 there emerged the present theory of strong interactions, QCD: Quantum ChromoDynamics. Each quark species, appetizingly called flavour, comes in three different varieties, with a Rimbaudian twist designated colours. (This is not just a case of 'Taking Three as the subject to reason about -/ A convenient number to state.' The concept of colour was first introduced to solve at the same time three different problems: the spin-statistics of the Δ particle, the lifetime of the neutral π , and the production ratio of hadrons in e^+e^- . Experimental data could be explained only if the number of colours was 'exactly and perfectly three.') The colour is the charge of the theory, and as mediators of the force there serve eight particles called gluons, carrying both colour and anti-colour. This latter fact is what makes the theory a non-abelian one: the gluons can interact with each other, and this interaction produces results that are very different from those obtained in the theory of electromagnetism, QED: Quantum ElectroDynamics.

In QED, the electric charge of the 'bare' electron is shielded by virtual electron-positron pairs. Analogously, the colour charge of the naked quark is modified by the influence of virtual quark-antiquark pairs, but also (and there's the rub) by virtual gluons; the effective coupling constant of QCD, α_s , will depend strongly on the distance (which can be otherwise described in terms of the energy scale squared, Q^2), viz. (to lowest order)

$$\alpha_s(Q^2) = \frac{12 \pi}{(33-2n_f) \ln \frac{Q^2}{\Lambda^2}}$$

where n_f is the number of flavours in the given energy regime, and Λ a parameter of the order of a few hundred MeV. At small distances, i.e. large Q^2 , α_s is small and so coloured objects feel almost no force: they are 'asymptotically free' and perturbative methods can be applied to compute their interactions. As the distance between them is increased, however, α_s grows and eventually the perturbation expansion breaks down. It is possible, although this has not been rigorously proven, that QCD might lead to the confinement of quarks, which would explain the failure of the aforementioned 'Hunting.' The colour field between a quark and an antiquark would, as the two were moved apart, be compressed into a colour flux tube of almost constant cross-section due to gluon self-interactions, and the force thus become constant. The quarks would be subjected to 'infrared slavery': as the distance between them increases, so does the energy needed to separate them further. Eventually, it will be energetically favourable to break the field by creating quark-antiquark pairs out of the vacuum - the confining field will fragment to give observable hadrons.

The real triumph of the quark concept came with the 'October revolution' of November 1974, when a new flavour, charm, predicted by the theory of weak interactions was experimentally found. On the other hand, the number of leptons - particles like the electron and the neutrino, sole survivors from the previous stratum of fundamentality - and quarks (allowing three colours to the flavour) had by then risen to 32; add to this eight gluons, the photon and the three intermediate vector bosons (needed in weak interactions) and the result is a veritable menagerie. The existence of yet another lepton and one further quark flavour (i.e. three new quarks) has since been established, and more particles are lurking in the new energy regime. This has again led theoreticians to consider the possibility of an underlying level of still more fundamental building-blocks, called preons, rishons, stratons and what-nots. 'Curiouser and curiouser!' -

perhaps the serpent is coiling up to bite his tail; perhaps the adversaries of Democritus will be finally vindicated and matter found to be infinitely divisible? Perhaps, but at present it is still possible within the framework of QCD to pose a 'three pipe problem', the investigation of which might, from time to time, lead to 'a trifling monograph.'

2. General Description

The method employed I would gladly explain,
While I have it so clear in my head,
If I had but the time and you had but the brain -
But much yet remains to be said.
Lewis Carroll: The Hunting of the Snark

Perturbative QCD offers us the possibility of describing hard processes, i.e. processes with a large momentum transfer. We can draw the Feynman diagrams contributing to a particular process and then apply the Feynman rules to calculate the corresponding amplitudes. We will thus know in what manner partons (quarks, gluons, etc.) are distributed after a reaction has taken place; however, experimental data do not relate directly to parton, but to final state hadron distributions. It has become increasingly obvious over the years that the hadronization process, i.e. the transformation of coloured constituents into observable colour neutral hadrons, plays an important rôle in the reaction. To be able accurately to predict the outcome of an experiment - to describe the complete event -, it is necessary to have a model for the fragmentation of partons into hadrons.

A possible starting-point for a phenomenological model of fragmentation is the assumption discussed in the Introduction, namely that particles are produced not by the constituents themselves, but by the colour force field that is spanned between them. When the partons move apart, they stretch the

connecting force fields, and these eventually break up, producing the final state hadrons. The confining force limits the transverse dimensions of the colour field, compressing it to an essentially one-dimensional structure: a colour flux tube or vortex line. The dynamics of this system can then be reasonably well modelled by the massless relativistic string, which has the further advantage of fulfilling the physical demands of Lorentz covariance and causality. One such model is the Lund model [1], the main feature of which is that it recognizes only triplet strings. Colour octets (e.g. gluons) are treated as kinklike excitations on the string: the force field is always stretched from colour triplet (quark or anti-diquark) to colour anti-triplet (antiquark or diquark) via the colour octets. This is the model we consider here.

Obviously, the particle distributions will depend on the exact topology of the force fields, different field configurations leading to different distributions. A given set of colour triplets, anti-triplets and octets can in general be connected in many different ways. Hence, a knowledge of the Feynman diagrams contributing to a given process will not suffice to specify unequivocally the final state. Rather, one has to start from the field topology. It has been shown in [2] how a given string configuration can be associated with a specific colour amplitude in a gauge invariant way. This connection can then be used to calculate the cross-section corresponding to any specified configuration of the colour fields.

Still, we are not prepared to make predictions and compare with data. Even the simplest of models can be hard to solve analytically if one wants to calculate quantities involving many particles. One way out of this predicament is to let a computer do a Monte Carlo simulation of complete events. A program is written that will generate the different hard processes according to their relative probabilities (as given by the QCD matrix elements), set up the colour field configurations, fragment the strings and let the unstable particles decay. The output of such a program can then be used for comparisons with experimental results.

In paper I we describe an event generator designed for the study of high- p_T physics. This program, PYTHIA, when run in conjunction with the Lund Monte Carlo for jet fragmentation [3], simulates all hard processes of order $\alpha_{em} \cdot \alpha_s$ and α_s^2 , and is the basic tool used in the studies of the subsequent papers. The paper contains a brief theoretical background and a calculation of the cross-sections for all possible colour field configurations in processes of $O(\alpha_{em} \cdot \alpha_s)$ and $O(\alpha_s^2)$; the main part, however, is dedicated to an exhaustive description of the program and how to use it.

In paper II, we examine the implications of colour field structure for a special case, the QCD Compton process. Here, a quark and a gluon react to give a quark and a photon. Since the photon does not partake of the strong interaction, the colour field configuration is particularly simple. Thus, a photon trigger ought to shed more direct light on the structure of confining force fields in hadron-hadron collisions than a hadron trigger. Our main result is that a study of the transverse momentum of the hadronic system can indeed tell us something about the nature of the confining field: the relative size of the p_T in-distributions (with p_T in the transverse momentum in the plane defined by the beam and the photon trigger) is a measure of how far out towards the endpoint partons the colour field is really stretched.

In paper III we try to resolve a question that has been around ever since jets were first seen: are they a product of trigger bias (demanding a single high- p_T particle) or can they be seen also using a calorimeter trigger? At the time of the study, experimental data [4] indicated that Nature prefers to create a large number of low- p_T particles to make up a large E_T -sum (the calorimeter trigger) and tends to disregard jets. However, there should exist a continuous relation between trigger acceptance (the solid angle of the calorimeter), center-of-mass energy and the fraction of triggers to come from hard constituent scattering (giving jets). Our approach is to consider the total transverse energy spectrum as built up from two parts: a soft contribution, simply given by the

multiplicity distribution convoluted with the transverse mass distribution, and a hard contribution caused by constituent scattering and calculated with the Monte Carlo of paper I. We then examine for what value of the transverse energy sum the constituent scattering mechanism starts to dominate for a given cms energy and trigger acceptance. The result is a simple formula:

$$\Sigma E_T(\text{cross-over}) = 12 \times \Delta y \times \frac{\Delta \phi}{2\pi} \text{ (GeV)}$$

if Δy is the rapidity and $\Delta \phi$ the azimuthal angle included in the calorimeter. This shows why [4] did (could) not see jets using the full calorimeter; more recent experiments at the collider [5] have confirmed our results qualitatively: the jets emerge as the calorimeter acceptance is decreased.

In paper IV we study the influence of the colour field on charm production. Since the charm quark mass is rather large ($1.2 - 1.6 \text{ GeV}/c^2$), its production in quark-antiquark annihilation and gluon-gluon fusion is a hard process, even at low p_T . However, experiments [6] measure a much harder x_F -spectrum for D-mesons than would be obtained from a calculation with the bare QCD matrix elements. We show, that the hard x_F -spectrum can be explained as an effect of the confining force field: the tension in the string pulls the c-quark outwards from the reaction centre and produces the observed distribution of D-mesons.

3. Outlook

Ah, but my Computations, People say...
Omar Khayyâm: Rubâiyât LVII

In this dissertation we have limited our study on implications of confining force field structures to a few cases with special triggers. The basic tool of the study has been the Monte Carlo program described in paper I; this can now be used

to investigate also other trigger situations. The first thing to do is obviously to produce a map of phase-space: a survey of the relative importance of different subprocesses and colour field configurations for different trigger conditions, such as trigger particle, p_T and azimuthal angle. A look at the map will tell us where in phase-space a particular trigger is likely to single out a specific subprocess. In this way it will be possible to study in more detail the characteristics of the colour field for each separate case.

One subprocess of particular interest is $qg \rightarrow qg$. Here, there exist two different colour field configurations, one 'open' and one 'closed' (cf. paper I). For pp-collisions, a high- p_T K^- is a good signature for the gluon emerging from this subprocess. However, using a K^- as a trigger has other implications as well. The $s\bar{s}$ -pair produced by the colour field at the gluon 'corner' to give a high- p_T K^- ($s\bar{u}$) has to be ordered along the direction of the field, i.e. the s-quark (a colour triplet) lies towards the anti-triplet end of the field, while the $\bar{s}$ antiquark (a colour anti-triplet) lies towards the triplet end. If we fix the direction of the K^- -trigger, we can then study the distribution of the associated strange particle, e.g. a K^+ ($\bar{s}u$), to find out how the colour field is stretched. Preliminary studies have indeed confirmed that it is possible to correlate the rapidity difference between the K^- and the K^+ to the direction of the colour field. This, and other investigations along the same line, will hopefully serve to unravel the structure of the stuff that holds the world together. As Sherlock Holmes so neatly puts it in the opening paragraph of Shoscombe Old Place: "It is glue, Watson," said he. "Unquestionably it is glue."

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References

- 1 B.Andersson, G.Gustafson, C.Peterson
Z.Physik C1 (1979) 105
B.Andersson, G.Gustafson
Z.Physik C3 (1980) 223
B.Andersson, G.Gustafson, T.Sjöstrand
Z.Physik C6 (1980) 235
- 2 G.Gustafson
Z.Physik C15 (1982) 155
- 3 T.Sjöstrand
Comp.Phys.Comm. 27 (1982) 243
- 4 C.De Marzo et al.
Phys.Lett. 112B (1982) 173
- 5 UA2 Collaboration, M.Banner et al.
Phys.Lett. 118B (1982) 203
- 6 LEBC EHS Collaboration, M.Aguilar-Benitez et al.
CERN/EP 82-203
LEBC EHS Collaboration, M.Aguilar-Benitez et al.
CERN/EP 82-204

